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Research Article

Structural diversity as an indicator of forest degradation in *Quercus robur* stands along the Tundzha river, Southeast Bulgaria

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Abstract

The structural integrity and compositional stability of *Quercus robur* dominated riparian forests in southeastern Bulgaria but have been increasingly compromised by long-term anthropogenic pressures, particularly hydrological modifications. This study investigates the structural diversity and regeneration dynamics of four representative stands along the Tundzha River, situated within protected areas and a strict reserve. Data were obtained through systematic plot-based sampling and analysed to evaluate diameter distribution, regeneration status, and radial growth patterns. Diameter distributions conformed predominantly to gamma and lognormal functions, indicative of uneven-aged stand structure in three of the four sites. Gini coefficients ranged from 0.39 to 0.58, reflecting varying degrees of structural heterogeneity. Regeneration of *Q. robur* was notably scarce across all stands, with understory layers largely dominated by shade-tolerant and competitive broadleaved species. This compositional trend is characterised by a consistent absence of oak in the smaller diameter classes and suggests a trajectory toward long-term replacement of oak by other species. Tree-ring chronologies further revealed a marked decline in radial growth beginning in the mid-20th century, coinciding with the onset of intensive flood control and drainage infrastructure. The results indicate that, despite retaining elements of structural complexity, these forests are undergoing gradual ecological degradation. The persistence of *Q. robur* in these systems is unlikely without targeted silvicultural measures aimed at promoting regeneration and mitigating the effects of altered hydrological regimes.

Key words: Ecological distribution, *Quercus robur*, Riparian mixed forests, structural complexity

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Introduction

Proportion of pedunculate oak (*Quercus robur* L) in the former lowland virgin forests varied over time due to climate fluctuations and changes in the hydrological regimes of river valleys. Over the past centuries, human activity played the most significant role in pedunculate oak forests decline, as lowland forests

were cleared for agriculture and timber (Zlatanov 2006). Progressive dieback has been the predominant form of pedunculate oak (*Quercus robur* L.) decline, posing a significant challenge in the practical management of oak stands. The key characteristics of this process include: (i) the dieback of old trees; (ii) a gradual loss of vitality preceding death, initially observed as reduced growth, followed by crown deterioration and symptoms of pathogenic attack, and (iii) the involvement of multiple abiotic and biotic factors that influence the process with varying intensity over different time periods (Dekanić 2014). The current deterioration of pedunculate oak populations, including the decline of individual trees and entire stands, is closely linked to long-term disruptions in moisture availability. These disruptions are primarily caused by flood control interventions and the implementation of surface drainage systems (Prpič 1996). Such interventions lower the water table, creating unfavourable conditions for pedunculate oak growth and often leading to a shift from wetland forests to drier forest types. According to Rauš et al. (1996), lowland pedunculate oak forests thrive when they transpire more water than they receive from rainfall, compensating for the deficit with additional moisture from floods and groundwater.

Across Europe, pedunculate oak forests have undergone a long-term decline, largely driven by land-use change, agricultural expansion, and intensive forest management. Once widespread across lowland and riparian landscapes, these forests are now highly fragmented, and old-growth stands are rare outside of protected areas (Leuschner and Ellenberg 2017). In many regions, their ecological functions have been diminished by conversion to more commercially productive or non-native tree species (European Environment Agency 2007). This pattern is mirrored in Bulgaria, where the area of pedunculate oak forests has been steadily decreasing for centuries. According to Velkov et al. (1991), large portions of the northern and southern Bulgarian plains were still covered by oak-dominated forests in the early 18th century. Today, only scattered remnants remain, primarily along the Tundzha River in southeastern Bulgaria and along rivers draining into the Black Sea and the Danube (Hinkov 2004). Chernyavski (1957) identified two main types of pedunculate oak forests along the Tundzha River. The first type, located along the lower river course, depended on a high water table and regular flooding. The canopy was dominated by pedunculate oak, accompanied by narrow-leaved ash (*Fraxinus oxycarpa* Willd.), European field elm (*Ulmus minor* Mill.), black poplar (*Populus nigra* L.), white willow (*Salix alba* L.), and occasionally common hornbeam (*Carpinus betulus* L.) and black alder (*Alnus glutinosa* Gaertn.). These forests suffered severe ecological disturbances due to overgrazing and acorn-feeding. The second type, found in the upper river course, occupied terraces formed by the Tundzha River and its tributaries. While these forests experienced high water tables in late autumn and spring, flooding was infrequent and short-lived. Intensive grazing significantly altered their structure as well, eliminating the understory and midstory layers and resulting in widely spaced, aging pedunculate oaks. The construction of modern hydro-technical infrastructure along the Tundzha River began in the mid-20th century. Two large reservoirs (Koprinka and Zhrebchevo) were built, serving as water storage for irrigation and electricity generation. Irrigation channels now divert much of the river's water away from its natural basin, depriving riverside vegetation of essential moisture. These reservoirs also retain most of the high spring water and, in conjunction with the continuous dykes along the river, prevent the periodic

flooding that once sustained the riverside ecosystems. Further disruption of the local water regime is caused by surface drainage canals.

The study aims to assess the structural diversity, including DBH distribution, regeneration, and growth potential of pedunculate oak-dominated forests along the Tundzha River, and to discuss the primary factors contributing to their decline.

Materials and methods

Regional and stand characteristics

The study area is located along the Tundzha River in the Gornotrakiiska and Tundzhanska valleys in Southeastern Bulgaria. Four stands (ST) were measured: two in the Tulovska Koriya Protected Site (ST1 and ST2), one in the Yulievska Koriya Protected Site (ST3), and one in the Gorna Topchiya Reserve (ST4) (Fig. 1). The area is located in the Continental–Mediterranean climatic region. In ST1 to ST3 the average annual temperature is 11 °C, with a summer mean of 20 °C and a winter mean of 1 °C. The average annual precipitation is 670 mm and the precipitation during the summer is 190 mm (Executive Forest Agency 2011). In ST4, the average annual temperature is 12 °C, with a summer mean of 21.5 °C and a winter mean of 2.5 °C. The average annual precipitation is 550 mm. Summers are long and dry, with total precipitation of 130 mm. The soils are alluvial, located on river terraces, with elevations of 326 m a.s.l. in ST1, 321 m in ST2, 311 m in ST3, and 123 m in ST4.

Methodological approach

To determine the structure of each stand, 25 circular sample plots were established in a square systematic grid, oriented along East–West and North–South axes. The distance between plot centres was set at 30 meters. A TruPulse 360B Laser Rangefinder (Laser Technology) was used to measure the distance and azimuth between plot centres. Each circular sample plot covered 100 m^2 (radius: 5.65 m). Within these plots, the species and diameter at breast height (DBH) of all trees with a DBH greater than 8 cm were recorded. In a smaller concentric circle of 25 m^2 (radius: 2.82 m), all trees with a DBH of 8 cm or less were measured. Within these smaller circles, regeneration by species was assessed in three height groups: up to 30 cm, 31–80 cm, and 81–130 cm. Additionally, at each plot centre, canopy closure was evaluated using a spherical densiometer (Englund et al. 2000).

A key aspect in analyzing the horizontal structure of forest stands is selecting the most appropriate probability distribution for tree diameters. Since the normal distribution only adequately describes tree diameter distribution during a specific stage of stand development, alternative distribution functions were tested. The statistical hypothesis was tested to determine whether the diameter distributions of the studied stands fit the following theoretical distributions: normal, lognormal, beta, gamma, Weibull, logistic, uniform, Poisson, and exponential. The Shapiro-Wilk test was used to determine which sample plots follow a normal distribution. For those plots where the null hypothesis of normality was rejected (p-value < 0.05), the most likely alternative distribution was identified using the Anderson-Darling test (Tonchev et al. 2020) and the fitdistr function from the MASS package (Venables and Ripley 2002). When multiple models

Figure 1. Location of studied sites: Tulovska Koriya ST1 (Lat: 25.552 Long: 42.567); Tulovska Koriya ST2 (Lat: 25.556 Long: 42.558); Yulievska Koriya ST3 (Lat: 25.596 Long: 42.566); Gorna Topchiya ST4 (Lat: 26.569 Long: 42.263).

were adequate, the Akaike Information Criterion (AIC) was used for model selection, with preference given to the model with the lowest AIC value. To assess the heterogeneity of the stands, the Gini index (*G*) was calculated using the Eq. (1):

$$G = \frac{\sum_1^n (2j - n - 1) g_j}{\sum g_j (n - 1)} \quad (1)$$

where: *gj* is the basal area of the tree with rank *j*; *j* is tree rank according to a diameter at breast height in ascending order 1, ..., *n*; *n* is total number of trees. The index quantifies the deviation from the perfect equality line with a minimum of zero and a theoretical maximum value of 1. The Gini index quantifies structural inequality within a stand, ranging from 0 (perfect equality) to 1 (maximum inequality). According to Duduman (2011) stands are categorized as follows: even-sized structure: G ≤ 0.35; two-sized: 0.35 < G ≤ 0.43; uneven-sized irregular: 0.43 < G ≤ 0.51; and uneven-sized balanced: G > 0.51.

A total of 59 tree-ring cores were collected from 4 sampling plots – 21 from Tulovska Koriya (ST1 and ST2), 20 from Yulievska Koriya (ST3) and 18 from the Gorna Topchiya (ST4). The cores were extracted at breast height (1.3 m) using an increment borer. The retrieved cores were mounted on wooden holders and subjected to sequential sanding with abrasive paper of 600 and 1200 grit, aiming to achieve smooth and clearly defined surfaces. Subsequently, the samples were digitized using a flatbed line scanner Epson Expression 11 000 XL with a resolution of 1200 DPI, and the measurement of tree-ring widths was performed using the specialized software CooRecorder (Larsson 2016). Cross-dating involved visual analysis for the identification of characteristic marker years and statistical assessment of the degree of correspondence between the time series, implemented through the software packages CDendro (Larsson 2016) and COFECHA (Grissino-Mayer 2001). To eliminate age-induced growth trends and isolate the climatic signal, various standardization procedures were

applied, implemented in the ARSTAN software package (Cook 1985). The primary detrending method employed was the approximation of the measured tree-ring widths with a negative exponential curve. In instances of unsuccessful detrending due to positive growth trends or the derivation of a negative approximating curve, linear detrending was applied. Additionally, as an alternative when the negative exponential curve did not fit the growth pattern, detrending was performed by applying a 67-percent spline filter.

Results

Stand structure

In all four stands, the gamma, lognormal, and Weibull distributions provided the best overall fit to the tree diameter data, although the degree of fit varied among the stands (Fig. 2, Table 1). In Tulovska Koriya (ST1), the lognormal and gamma distributions performed best, consistently showing lower AIC values than other models. Tulovska Koriya (ST2) showed a good fit for both the lognormal and Weibull distributions, indicating a moderately right-skewed diameter structure. Yulievska Koriya (ST3) had the best fit with the lognormal and gamma distributions, effectively capturing its highly skewed diameter distribution. In Gorna Topchiya (ST4), although none of the distributions showed a statistically significant fit, the uniform distribution had the lowest AIC, followed closely by the normal and Weibull distributions, suggesting a more balanced or irregular diameter pattern. Overall, the lognormal and gamma distributions proved to be

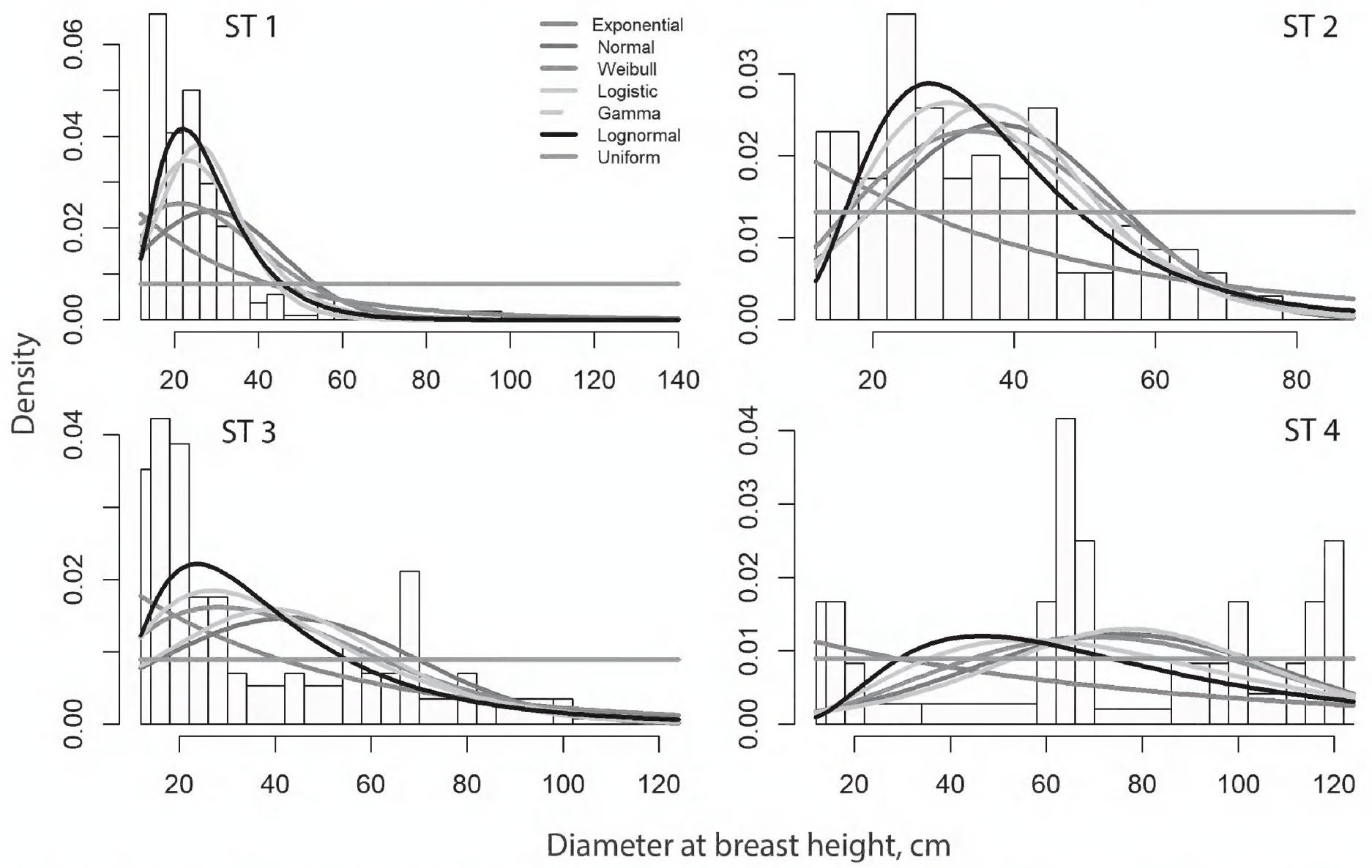

Figure 2. Fitting distribution curves – including Exponential, Normal, Weibull, Logistic, Gamma, Lognormal and Poisson – to the diameter of breast height distribution of the trees in the sample plots. Tulovska Koriya ST1; Tulovska Koriya ST2; Yulievska Koriya ST3; Gorna Topchiya ST4.

Table 1. Values of Akaike Information Criterion for fitted distribution curves and Gini coefficients. Tulovska Koriya ST1; Tulovska Koriya ST2; Yulievska Koriya ST3; Gorna Topchiya ST4.

Distribution	ST1	ST2	ST3	ST4
Normal	1149	741	674*	298
Weibull	1097	732	653	299
Logistic	1078	742	677*	300
Uniform	1306	748*	669*	285*
Gamma	1051	726	649*	304
Poisson	1630	1089*	1532*	665*
Exponential	1177	808*	677*	322*
Lognormal	1018	725	644	310
Gini coefficient	0.39	0.54	0.45	0.58

*non significant.

the most flexible and consistent across different stand structures, while the Poisson and exponential models performed poorly in all cases. The Gini index, also varied across the sample plots as follows: Tulovska Koriya 1: Gini = 0.54; Tulovska Koriya 2: Gini = 0.45; Yulievska Koriya: Gini = 0.58; Gorna Topchiya: Gini = 0.39. The canopy closure was very high – averaging between 0.8 and 0.9 (with 1 indicating full closure) – across all four studied stands, with fewer than 5% of the plots having canopy closures below 0.7.

The diameter at breast height (DBH) distribution of trees ≥8 cm in the four sample plots (Fig. 3) reveals substantial variation in species composition across the different diameter classes. While *Quercus robur* dominates the upper size classes (≥ 30 cm), it is nearly absent from the smaller diameter classes (10–30 cm), which are almost entirely occupied by other broadleaved species. Those include: in Tulovska Koriya (ST1 and ST2) – *Carpinus betulus*, *Acer campestre* L., *Ulmus minor* solitary (sol.), *Prunus avium* L. sol., *Populus alba* L. sol., *Prunus cerasifera* Ehrh. sol., *Tilia platyphyllos* Scop. sol. and *Acer tataricum* L.; in Yulievska Koriya (ST3) – *Acer campestre*, *Acer monspessulanum* L., *Malus sylvestris* Mill. sol., *Prunus cerasifera* sol. and *Fraxinus angustifolia* Vahl sol.; in Gorna Topchiya (ST4) – *Ulmus minor*, *Acer campestre*, *Acer tataricum* sol. and *Fraxinus angustifolia* sol. This pattern indicates that oak, although currently dominant in the overstory, is failing to recruit successfully under current conditions in all studied stands. This trend is especially pronounced in Yulievska Koriya (ST3) and Gorna Topchiya (ST4), where oak is completely missing from the smallest DBH classes, In contrast, Tulovska Koriya (ST1 and ST2) still retain some oak presence in the lower diameter classes, particularly in ST2, where recruitment appears marginally more successful. However, even in these plots, other species are better represented in the smaller size classes. The observed patterns point toward a gradual shift in forest composition.

Regeneration

Across all sample plots, the regeneration layer is dominated by non-oak species. Although *Quercus robur* remains a key component of the overstory, it is notably scarce in the regeneration strata (Fig. 4). This pattern is consistent across all

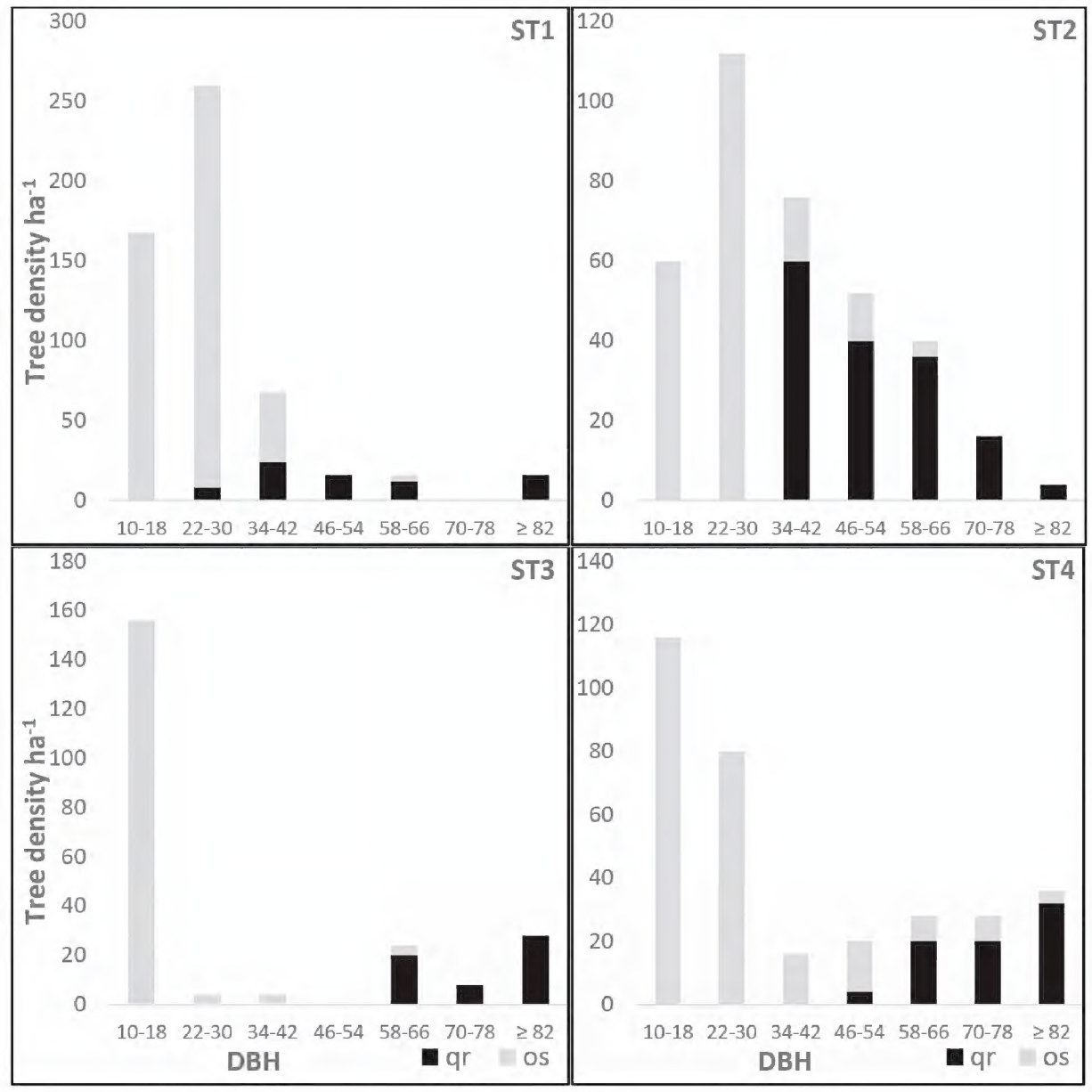

Figure 3. Species density of the trees by diameter at breast height classes: QR – *Quercus robur*; OS – other species. Tulovska Koriya ST1; Tulovska Koriya ST2; Yulievska Koriya ST3; Gorna Topchiya ST4.

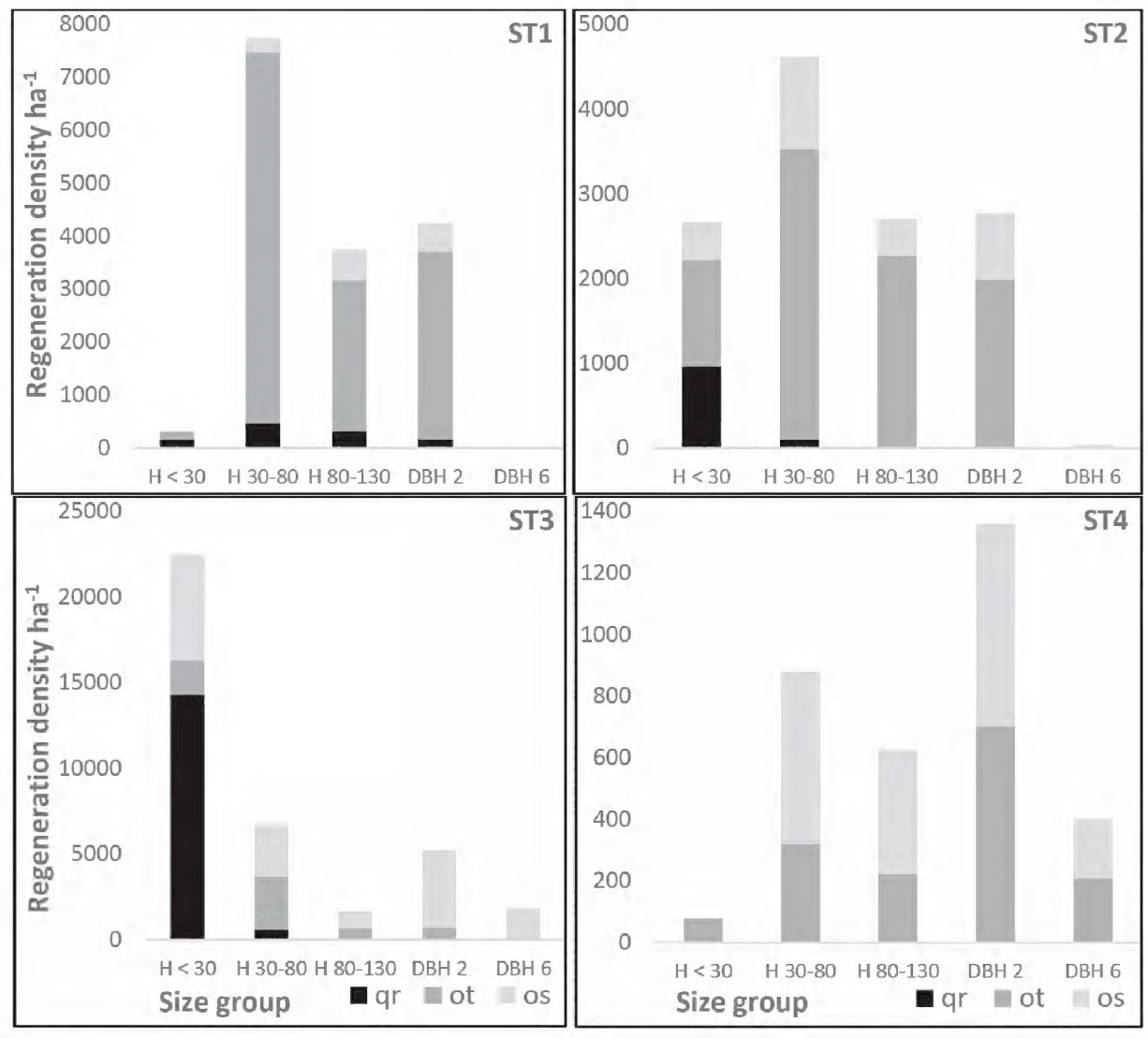

Figure 4. Species density of the regeneration by size groups: QR – *Quercus robur*; OT – other tree species; OS – other shrub species. Tulovska Koriya ST1; Tulovska Koriya ST2; Yulievska Koriya ST3; Gorna Topchiya ST4.

height levels and early DBH ranges–from seedlings under 30 cm in height to saplings with diameters up to 6 cm – highlighting oak's ongoing failure to recruit successfully. In contrast, other broadleaved tree species and shrubs are regenerating in large numbers and are well represented across all size groups. These include: ST1 and ST2 – *Corylus avellana* L., *Crataegus monogyna* Jacq., *Euonymus europaeus* L., *Ligustrum vulgare* L., *Cornus sanguinea* L., *Rosa* sp., and *Prunus spinosa* L.; ST3 – *Corylus avellana*, *Crataegus monogyna*, *Euonymus europaeus*, *Ligustrum vulgare*, *Cornus sanguinea*, and *Rosa* sp. and ST4 – *Cornus sanguinea*, *Crataegus monogyna*, *Euonymus europaeus*, *Ligustrum vulgare*, and *Sambucus nigra* L. Their presence across multiple size classes suggests not only successful establishment but also progression toward eventual inclusion in the main canopy. This trend is particularly pronounced in Yulievska Koriya (ST3), where total regeneration density exceeds 24,000 individuals ha^{-1}, yet oak contributes only marginally, with nearly all regeneration stratum composed of other tree and shrub species. A similar pattern is evident in Tulovska Koriya ST1 and ST2, where oak regeneration remains sparse across all size groups, while other species – especially shade-tolerant trees and shrubs – dominate even the larger sapling classes (2–6 cm DBH). In Gorna Topchiya (ST4), overall regeneration density is lower, yet the composition still favors non-oak species, with the oak playing only a minimal role.

Radial growth

The longest core sample obtained contained 135 tree rings, indicating that the corresponding tree in the Yulievska Koriya (ST3) site germinated shortly before the year 1885. In the Tulovska Koriya (sites ST1 and ST2), the oldest tree sampled was approximately 100 years old. At the Gorna Topchiya site (ST4), the oldest recorded tree began growing in around 1920. The composite tree-ring chronologies developed for these sites contain data from more than five core samples after the year 1950. Specifically, the chronologies extend back to 1930 and 1919 for Tulovska Koriya (ST1 and ST2), Yulievska Koriya (ST3), and Gorna Topchiya (ST4) (Fig. 5). Across all the sites investigated, a notable

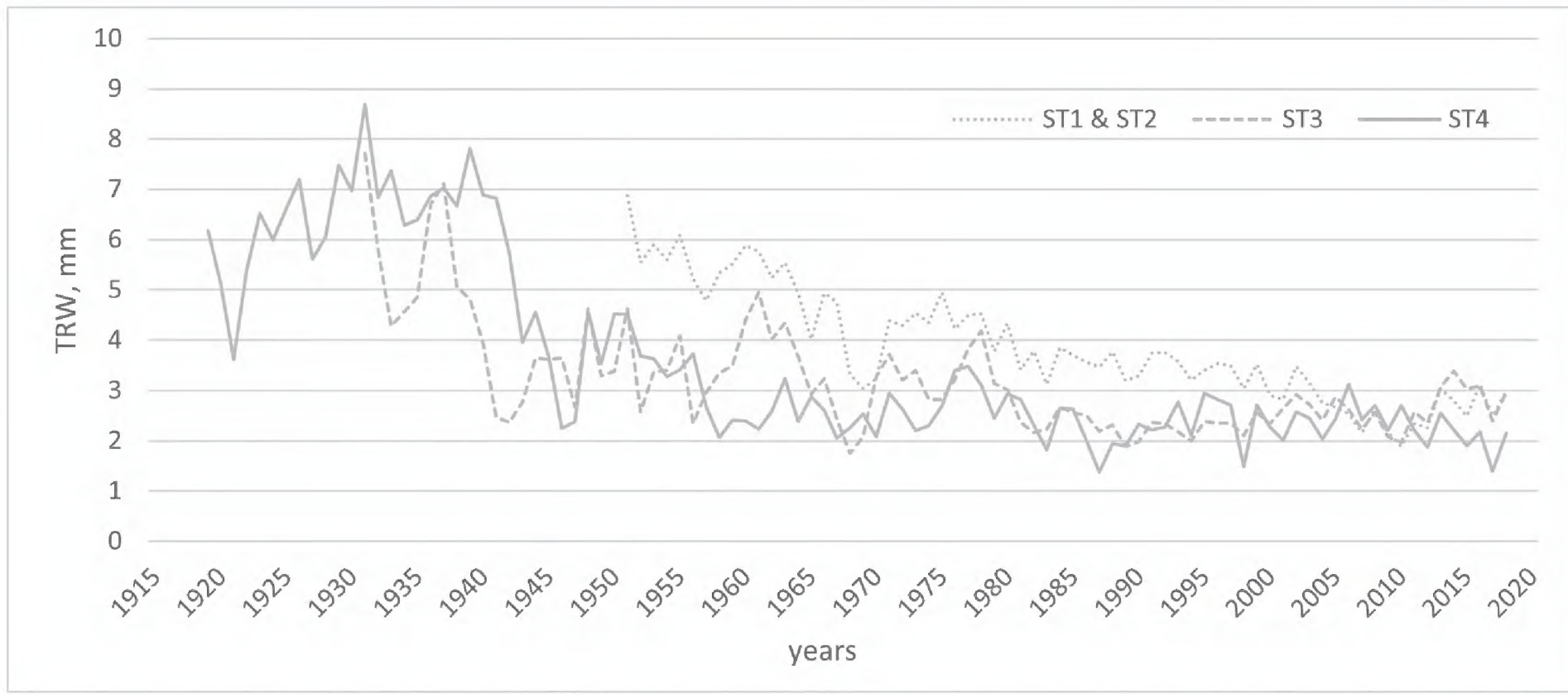

Figure 5. Tree ring width (TRW) chronologies for Tulovska Koriya (ST1 and ST2), Yulievska Koriya (ST3), and Gorna Topchiya (ST4).

decrease in radial growth was observed. These declining trends become particularly evident in the late 1930s and early 1940s for the Yulievska Koriya (ST3) and Gorna Topchiya (ST4) sites, and later, in the 1960s, for the trees in the Tulovska Koriya area (ST1 and ST2). The tree-ring characteristics varied across the studied sites. In Tulovska Koriya (ST1 and ST2), the mean tree-ring width was the highest at 4.01 mm (with a range of 0.59–13.53 mm), accompanied by a mean sensitivity of 0.198 and a first-order autocorrelation of 0.73. Yulievska Koriya (ST3) showed a slightly lower mean tree-ring width of 3.16 mm (range: 0.38–25.76 mm), but the highest mean sensitivity at 0.230 and a first-order autocorrelation of 0.71. Gorna Topchiya (ST4) had a similar mean tree-ring width of 3.21 mm (range: 0.36–17.95 mm) to Yulievska Koriya, with a mean sensitivity of 0.210 and a first-order autocorrelation of 0.71.

Discussion

The consistent performance of the gamma and lognormal distributions in fitting diameter data of the studies stands aligns with their established flexibility in modelling forest stand structures, which are often right-skewed due to the dominance of smaller diameter trees and fewer large individuals (Pretzsch 2009; Weiskittel et al. 2011). The prevalence of these distributions in Tulovska Koriya 1, Tulovska Koriya 2, and Yulievska Koriya underscores the uneven-aged, multi-cohort nature of these stands. The relatively high Gini indices, reflecting inequality in tree diameter distribution and structural heterogeneity in Tulovska Koriya 1 (0.54) and Yulievska Koriya (0.58), further support this interpretation, indicating substantial size inequality typical of uneven-aged, structurally complex forests (O'Hara et al. 2007). Gorna Topchiya had the lowest index value (0.39), suggesting a two-sized structure with moderate variation in tree sizes. Accordingly, three of the four stands in this study are classified as "uneven-sized" (uneven-aged) according to Duduman (2011), while the Gorna Topchiya plot is considered "two-sized" (two-aged). It should be noted, however, that in some even-aged stands, an increase in the Gini index may still occur due to the development of a second cohort of trees (O'Hara et al. 2007). The forests in the current study can be more closely associated with this latter group, the old pedunculate oak trees gradually being replaced by associated species with significantly smaller diameters. This interpretation is supported by the consistently high canopy closure observed across all four studied stands and nearly all subplots. This carries important implications for future stand development. High Gini values – especially in stands with poor *Quercus robur* recruitment – may signal ongoing compositional shifts toward more shade-tolerant or competitive species. In areas where oak regeneration is absent (e.g., Yulievska Koriya and Gorna Topchiya), increased size inequality may reflect the success of other species in occupying vertical growing space and establishing persistent regeneration layers. In contrast, balanced but oak-deficient structures such as stands in Tulovska koriya may indicate a transitional phase, in which legacy oak individuals persist in the overstory while other species dominate the understory, setting the stage for future canopy replacement.

The forests of pedunculate oak (*Quercus robur*) with common hornbeam (*Carpinus betulus*) have long been recognized in phytocoenological literature as a distinct association – *Carpino betuli – Quercetum roburis* – widely distributed

across the Balkan Peninsula, particularly in river terraces and lowlands free from frequent flooding (Anic 1959; Rauš et al. 1996). These forests, typically located in areas with stable moisture conditions, are dominated by oak with hornbeam present in the canopy. The shrub layer comprises species such as *Corylus avellana*, *Euonymus europaea* and *Crataegus monogyna* (Rauš et al. 1996). The stands in Tulovska Koriya (ST1 and ST2) closely align with this association in terms of tree and shrub composition, although degradation processes were evident, particularly in ST1, where *Quercus robur* had been largely replaced by *Carpinus betulus*, both in the overstorey and understorey. The presence of *Fraxinus angustifolia* and the lack of hornbeam in the stands in Yulievska Koriya (ST3) and Gorna Topchiya (ST4) implies that, in an ecological sense, they are much closer to the next, more humid association. It is described as *Genisto elatae – Quercetum roburis* Ht., 1938 (Rauš et al. 1996). Stands occur on wide, flat river terraces, found immediately along large rivers. In natural, undisturbed conditions these terraces are periodically flooded. Floodings, to which hornbeam is very susceptible, normally last for short periods. However, due to amelioration activities regular floods have been absent even in this more humid association for the last 60–80 years, which has led to extensive spread of *Acer tataricum*. This species usually appears on the borders of phytocoenoses, from drier towards wetter positions: where the common hornbeam "diminishes", Tatarian maple "appears" (Rauš at al. 1996; Bobinac 2000, 2011). In undisturbed conditions in both associations, the dominance of pedunculate oak in the understorey species composition is related particularly to occurrence of regular short floods as oak seedling and sapling tolerate short floods to a higher extend compared to its associated species (Zlatanov 2006). Alaoui-Sosse et al. (2005) demonstrated that pedunculate oak seedlings tolerate short-term flooding. Under controlled conditions, seedlings were flooded for 34 days, resulting in a 66% reduction in root biomass compared to controls. Fourteen days after drainage, lateral root biomass recovered to 98% of control levels, though tap root biomass remained lower. Leaf area and root length were significantly reduced during flooding but returned to near-control values after drainage, while shoot growth was unaffected.

Similar patterns of high structural complexity combined with declining oak regeneration have been reported in lowland mixed forests in western Romania (Abrudan et al. 2009), where pedunculate oak struggles to regenerate under closed canopies dominated by shade-tolerant competitors such as *Carpinus betulus* and *Tilia cordata* Mill. As Johnson et al. (2002) report, unlike more xerophytic oak species, pedunculate oak frequently fails to regenerate due to its vulnerability to successional displacement by the more shade-tolerant species with which it typically co-occurs. Nevertheless, in pedunculate oak forests, reproduction through seeding is considered a more critical regeneration strategy than in many other oak-dominated communities, where sprouting typically plays a dominant role (Zlatanov 2006). The significance of seeding as a regeneration mechanism is often demonstrated following mast years, during which a substantial number of seedlings become established. For instance, in pedunculate oak forests in Croatia, managed under a shelterwood system, up to 50,000 oak seedlings may establish after a particularly heavy acorn crop (Matič 1996). However, in the case of the current study, the insufficient presence of oak seedlings and saplings in the studied stands prevents us from recommending any

standard silvicultural treatments. Under such conditions – permanent change of water regime and subsequent development of dense overstorey of competing tree and shrub species, planting pedunculate oak seedlings, preceded by canopy openings, mechanical removal of competing species and soil preparation, may be the most viable option for regenerating oak.

Lowland pedunculate oak forests are sensitive to groundwater levels. Typically, these types of forests have good radial growth when they can compensate for moisture deficits with the help of groundwater or periodic flooding (Rauš et al. 1996). Pedunculate oak is a long-lived species, known to reach ages of several hundred years. Considering that the stands we studied were approximately under and around 50 years old at the time of recording reduced radial growth (fig. 5), and the hydro-technical infrastructures were built only about 10 years ago, it is unlikely that the natural aging process alone can fully explain the observed decline. A key factor to consider is pedunculate oak's hygrophilous nature. This species is particularly sensitive not just to atmospheric moisture deficits but, more critically, to reductions in groundwater availability (Leuschner and Ellenberg 2017). The construction of the hydro-technical infrastructures and their associated flood control measures and surface drainage systems would directly impact the hydrological regime of these riparian forests. Such modifications can lead to a lowering of the water table or altered flooding patterns, which could induce stress and contribute to the observed growth decline. Therefore, while aging might play a minor role, we hypothesize that the hydrological alterations caused by the dam construction are a significant contributing factor to the observed decline indications. In addition, the use of these types of forests for grazing leads to soil compaction and a reduction in its permeability to rainfall (Donovan and Monaghan 2021). Intensive grazing, on the other hand, leads to a limitation of grass vegetation, which is a prerequisite for faster water loss in the surface layers of the soil (Eldridge et al. 2022).

In conclusion, the stand structural analysis and regeneration assessment reveal a system in decline. While elements of structural complexity persist, particularly in terms of uneven diameter distributions and moderate to high Gini coefficients, these are not indicative of healthy or resilient forest dynamics. Rather, they reflect a senescing cohort of overstorey oaks with minimal recruitment, increasingly replaced by shade-tolerant or opportunistic species in the regeneration layer. The absence of oak regeneration across all studied sites, combined with declining radial growth trends, suggests that these forests are undergoing a compositional shift that, if unaddressed, may become irreversible. The principal driver of this degradation appears to be the disruption of natural hydrological regimes. The construction of reservoirs, irrigation channels, and flood control infrastructure has eliminated the periodic flooding historically essential for Q. robur regeneration. In this altered context, oak seedlings are unable to establish or persist, while more shade-tolerant species gradually dominate the understorey. To halt and reverse this trajectory, a combination of ecological restoration and silvicultural intervention is required. Priority should be given to the restoration of at least partial hydrological connectivity, including seasonal inundation where feasible, to recreate conditions favourable for oak establishment. Additionally, active reforestation using *Q. robur* seedlings should be undertaken, ideally in conjunction with canopy openings and removal of competing undergrowth.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

Conceptualization: TZ. Data curation: NT, GHH, TT, MZ. Formal analysis: TZ, NT, TT. Project administration: MZ. Writing – original draft: TZ. Writing – review and editing: TT, NT, GG, GHH.

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Data availability

All of the data that support the findings of this study are available in the main text.

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